Implication of the observable spectral cutoff energy evolution in XTE J1550-564

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ABSTRACT

The physical mechanisms responsible for production of the non-thermal emission in accreting black holes should be imprinted in the observational apperances of the power law tails in the X-ray spectra from these objects. Variety of spectral states observed from galactic black hole binaries by it Rossi X-ray Timing Explorer (RXTE) allow examination of the photon upscattering under different accretion regimes. We revisit of RXTE data collected from the black hole X-ray binary XTE J1550-564 during two periods of X-ray activity in 1998 and 2000 focusing on the behavior of the high energy cutoff of the power law part of the spectrum. For the 1998 outburst the tran- sition from the low-hard state to the intermediate state was accompanied by a gradual decrease in the cutoff energy which then showed a sharp reversal to a clear increasing trend during the further evolution towards the very high and high-soft states. However, the 2000 outburst showed only the decreasing part of this pattern. Notably, the photon indexes corresponding to the cutoff increase for the 1998 event are much higher than the index values reached during the 2000 rise transition. We attribute this difference in the cutoff energy behav- ior to the different partial contributions of the thermal and non-thermal (bulk motion) Comptonization in photon upscattering. Namely, during the 1998 event the higher accretion rate presumably provided more cooling to the Comptonizing media and thus reducing the effectiveness of the thermal upscattering process. Under these conditions the bulk motion takes a leading role in boosting the input soft photons. Monte Carlo simulations of the

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Comptonization in a bulk motion region near an accreting black hole by Laurent & Titarchuk (2010) strongly support this scenario. strongly support this scenario.

Subject headings: accretion, accretion disks—black hole physics—stars: individual (XTE J1550-564):radiation mechanisms: non-thermal—physical data and processes

1. Introduction

The main feature of the X-ray spectrum observed from an accreting black hole (BH) is a strong non-thermal component phenomenologically described by a power law with exponential cutoff at energies above 20 keV. The origin of this emission is attributed to multiple Compton upscattering of the soft photons off energetic electrons present near the central object. The balance between thermal and non-thermal components in a source spectrum is the primary parameter used to define the BH spectral state. A low luminosity state with an essentially non-thermal spectra is called as the low-hard state (LHS), while the state where the thermal component of color temperature around 1 keV dominates is called as the high-soft state (HSS). Transitions between these two states are classified as the intermediate state (IS). During rare episodes, when an accretion rate presumably reaches the Eddington limit, these non-thermal and thermal components appear strong in the source spectrum. These episodes are identified with the very high soft state (VHS) (see Remillard & McClintock 2006; Belloni 2005; Klein-Wolt & van der Klis 2008, for different flavors of BH states definitions). Constraining the nature of the spectral energy cutoff of the power law component is essential for understanding the processes occurring in the immediate vicinity of the accreting BHs.

Until recently, the observational picture on the extended spectral tails in galactic BH X-ray binaries was based largely on the OSSE results presented by Grove et al. (1998). The main conclusion of this work is that in LHS the power law has a clear cutoff at ~ 100 keV, while the HSS tails are steep and show no overturn at the high energies. Presence of the non-thermal electron population was proposed as an explanation by the authors. Latest observational findings, however, reveal much more detailed picture of the cutoff energy behavior. Recently Motta et al. (2009) pointed out the specific pattern in the high energy cutoff evolution during LHS-to-HSS spectral transition in GX 339-4. Namely, authors report the monotonic decrease of the cutoff from 120 keV in LHS to 60 keV in the IS and then its sharp increase during the transition to HSS. They also pointed out the intimate connection of the cutoff energy and the fast variability in the source lightcurve. The results by Motta et al. (2009) along with the cutoff energy behavior in XTE J1550-564 reported here present much more detailed cutoff phenomenology due to the RXTE frequent monitoring campaigns. These results show, in particular, that the cutoff energy exhibits gradual evolution from LHS to HSS, which hard to reconcile with a simple no-cutoff picture for HSS set forth by Grove et al. (1998).

An extended power law distribution of photons with respect to energy is a natural consequence of a repetitive scattering of the "seed" input photons off energetic electrons. If electrons can be considered as having Maxwellian energy distribution, then Comptonization is said to be thermal and the resulting power law has a high energy turnover at the energy approximately twice of the temperature of Comptonizing electrons (Hua & Titarchuk 1995). While the thermal Comptonization is able to explain spectral properties of accreting black holes in LHS, it has difficulties in the case of HSS. To account for the steep extended power-law tail one needs to invoke geometrical configurations for the Comptonization region with temperatures kT_e of 100-150 keV and optical depths of 0.1, which is arguably very unstable [see Titarchuk & Lyubarskij (1995), Borozdin et al. (1999)]. On the other hand, Laurent & Titarchuk (1999), hereafter LT99, showed that these steep power-law photon distributions (with photon index higher than 2.0) are produced in the convergent flow into compact objects when infalling plasma temperature does not exceed 10 keV. The characteristic feature of these spectra is the abrupt cutoff at the energy of the order of 511 keV ($m_e c^2$, where m_e is the electron mass and the speed of light respectively) and can be modeled by an exponential cutoff with the folding energy in the range of 200−400 keV.

In Shaposhnikov & Titarchuk (2009, hereafter ST09) we present observational evidence that the bulk inflow motion phenomenon is imprinted in the correlation pattern of the spectral and variability properties in the form of the photon index saturation effect. It was shown that in IS state, when the thermal and bulk motion Comptonization (BMC) are equally important, the index depends strongly on mass accretion rate $\dot{M}$, indicated either by normalization of the spectral continuum or by the frequency of quasi-periodic oscillations (QPOs). However, in HSS spectral index tends to saturate. In this state high mass accretion rate provides an effective cooling for a Comptonizing region. Therefore, the BMC effect should take over the thermal process. It was shown analytically and numerically that spectral index of the radiation spectrum resulting from the BMC in a cold converging inflow does not depend on the $\dot{M}$ for high mass accretion rates [Titarchuk & Zannias (1998), LT99]. In fact, ST09 demonstrate this saturation effect versus mass accretion rate $\dot{M}$ (both QPO frequency and spectrum normalization used as a proxy for $\dot{M}$) in a number of galactic BH candidates including XTE J1550-564.

In this Paper we study, in detail, a particular behavior of the energy spectrum observed by *RXTE* from the galactic BH candidate XTE J1550-564 during two outbursts occurred in 1998 and 2000. Specifically, we concentrate on the behavior of the high energy cutoff of the power law spectral component. These two events were significantly different in strength, with the latter outburst being much weaker and shorter in duration. During the 1998 outburst the source started out off LHS, evolving through IS and reached VHS during an extremely bright flare. The source then returned to IS and transited into HSS later on [Sobczak et al. (2000), ST09]. The high energy cutoff evolution during this episodes is completely consistent with pattern reported by Motta et al. (2009) for the hard-to-soft transition in GX 339-4 in 2007. On the other hand during the 2000 event the source did not exhibit VHS and the peak flux was five times lower than that during the 1998 outburst. We find similarities and differences in the behavior of the high energy part of the spectrum during these two events. We explain the observed evolution of the cutoff folding energy E_{fold} by the varying contribution of the thermal and bulk motion Comptonization processes in the upscattering the input soft photons. We find that the cutoff phenomenology is in excellent agreement with the scenario when thermal and bulk motion Comptonization processes dominate LHS and HSS correspondingly, while in IS both processes are equally important in boosting the low energy photons.

In the next section we describe the data reduction and analysis. In §3 we offer the interpretation of the power-law efold energy (E_{fold}) evolution in terms of interplay between thermal and non-thermal (bulk motion) Comptonization. Discussions and conclusions follow in §4 and §5 respectively.

2. Observations and data reduction

We use archival *RXTE* data from the HEASARC[1]. For 1998 outburst we analyzed data from 64 pointed observations starting with the first pointed *RXTE* observation of the source on September, 7 1998 (MJD 51063.67) and ending on November, 2 1998 (MJD 51119.0), when the source have completed the transition to HSS. For the 2000 event we analyzed 47 pointed observations starting on April 10, 2000 (MJD 51644.5) and ending on June 11, 2000 (MJD 51706.0), when the source was in the LHS decay. The first comprehensive analysis of 1998 and 2000 outbursts from XTE J1550-564 was presented in Sobczak et al. (2000). We refer a reader to this paper for the exhaustive account of the data and general phenomenology.

RXTE/PCA spectra have been extracted and analyzed in the 3.0-50 keV energy range using the most recent release of PCA response calibration (ftool `pcarmf v11.7`). The rele-

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[1]http://heasarc.gsfc.nasa.gov/

vant deadtime corrections to energy spectra have been applied following "The RXTE Cook Book" recipe. HEXTE spectra were extracted and analyzed in 20-250 keV energy range. The PCA and HEXTE energy spectra were modeled jointly using XSPEC 12.0 astrophysical spectral analysis package. To fit PCA spectra we used the sum of the *bmc* component (Generic Comptonization model, see Titarchuk, Mastichiadis & Kylafis 1997) and a Gaussian with the energy ~ 6.5 keV, which is presumably related to iron emission line. This model was also modified by the interstellar absorption, using the *wabs* model in XSPEC, with a hydrogen column value fixed at the Galactic value given by nH HEASARC tool (Dickey & Lockman 1990) and by a high energy cut-off (*highecut*). The upper limit of 1.2 keV was applied to the width of the Gaussian. The high energy cutoff component accounts for the exponential overturn of the spectrum. Systematic error of 1.0% have been applied to the analyzed spectra.

The *bmc* model describes the outgoing spectrum as a convolution of input "seed" black body spectrum having normalization N_{bmc} and color temperature kT with a Green function for Comptonization process. Similarly to the ordinary *bbody* XSPEC model, the normalization N_{bmc} is a ratio of BB luminosity (BB seed photon luminosity) to square of the distance

$$N_{bmc} = \left(\frac{L}{10^{39}\mathrm{erg/s}}\right)\left(\frac{10\,\mathrm{kpc}}{d}\right)^2. \tag{1}$$

The resulting model spectrum is also characterized by a parameter $\log(A)$ related to a Comptonized fraction f where $f = A/(1+A)$ and the Green's function spectral index $\alpha = \Gamma - 1$ where Γ is photon index.

There are two reasons for using the *bmc* model. First, *bmc* by the nature of the model is applicable to the general case when photons gain energy not only due to thermal Comptonization but also via dynamic or bulk motion Comptonization (see LT99, Titarchuk, Mastichiadis & Kylafis 1997; Shaposhnikov & Titarchuk 2006, for details). The second reason is that *bmc* calculates consistently the normalization of the "seed" photons N_{bmc}, presumably originated in the disk. The relation of N_{bmc} and its possible proportionality to the mass accretion rate in the disk is related to the accretion disk theory (see e.g. Shakura & Sunyaev 1973). The adopted spectral model describes well the most data sets used in our analysis. The value of reduced χ^2-statistic $\chi^2_{red} = \chi^2/N_{dof}$, where N_{dof} is the number of degrees of freedom for a fit, is less or around 1.0 for most of the observations. For a small fraction (less than 3%) of spectra with high counting statistic the value of χ^2_{red} reaches 1.5. However, it never exceeds a rejection limit of 2.0.

3. Evolution of the spectral properties during state transitions in XTE J1550-564

We present an evolution of the relevant spectral parameters for the 1998 and 2000 outbursts in Figures 1 and 2 correspondingly. Different spectral states are separated by color legend. In Figure 3 we illustrate the spectral evolution in XTE J1550-564 from LHS to soft states (HSS and VHS) through IS.

The 1998 outburst of XTE J1550-564 developed as follows. The outburst started on MJD 51063 and went through the initial LHS and then entered the hard IS. Energy E_{fold} dropped from 100 keV to 50 keV during this LHS-IS phase. In Figure 1 this stage is marked by filled black circles. The source exhibited a strong flare on MJD 51076, when photon index peaked at 2.8 (IS-VHS) marked by red points. On the other hand E_{fold} showed sharp peak up to 250 keV during the flare. We indicate these data by red color. After the flare the source returned to IS with index $\sim 2.1 - 2.2$ and E_{fold} dropped back to 50 keV. For the following 20 days we observed smooth evolution toward HSS with index slightly increasing to ~ 2.4 (blue is used for for IS-HSS transition data). That is important to note that there is a steady upward trend in E_{fold} during this period, accompanied by slow decrease of the Comptonized fraction. On about MJD 51105 the source entered HSS, when E_{fold} jumped to 150-200 keV range (see red points in Fig. 1). During the IS-HSS stage the source presumably went through the strong surge of accretion. This cold accretion flow provided strong photon cooling for the innermost part of the accretion flow which is manifested by an increase of spectral index.

The behavior of the source during the 2000 outburst was clearly different (see Figure 2). First, there was no VHS flare and the maximum flux reached for this outburst was five times less than that at the maximum for the 1998 event. The initial LHS and hard IS are indicated by black data points from MJD 51644 to MJD 51659. During this state we observe a decrease of E_{fold} energy similar to 1998 outburst LHS-IS stage, however, reaching down only to 100 keV values apart to the 50 keV bottom plateau during 1998 event seen in Fig. 1. No apparent increase of E_{fold} is seen for the transition to HSS on MJD 51660. Much lower overall flux observed during this outburst is probably indicating a much lower mass accretion rate in the disk with respect to that during the 1998 event. This is also clearly reflected in behavior of the source spectrum. Namely, index does not grow higher than 2.0 but E_{fold} stays high. This is presumably due to the constant presence of the hot thermal Comptonizing media throughout the transition. *The level of cold matter supply in the disk is not sufficient to completely cool down Compton Cloud in the case of 2000 outburst.*

4. Discussion

LT99 studied the Comptonization of the soft radiation in the converging inflow (CI) into a black hole (BH) using Monte Carlo simulations. The full relativistic treatment has been implemented to reproduce the spectra. LT99 show that spectrum of the soft state of BHs can be described as the sum of a thermal (disk) component and the convolution of some fraction of this component with the CI upscattering spread (Greens) function. The latter is seen as an extended power law at the energies much higher than the characteristic energy of the soft photons and plasma temperature. LT99 demonstrate the stability of the power-law index (the photon index $\Gamma \sim 2.8$) over a wide range of the plasma temperature 0−10 keV and mass accretion rates (higher than 2 in Eddington units) due to upscattering and photon trapping in the CI. However the spectrum is practically the same as that produced by standard thermal Comptonization when the CI plasma temperature is of order 50 keV (the typical ones for the BH hard state) and photon index is around 1.7. LT99 also demonstrate that the change of the spectral shapes from the soft state to the hard state is clearly related to electron temperature T and optical depth of the bulk inflow τ [see also Titarchuk, & Fiorito (2004) for more details of the $T - \tau$ dependence]. When mass accretion rate of the flow increases the plasma temperature decreases and thus the high energy cutoff E_{fold} decreases until the effects of bulk motion Comptonization become dominant. Then a value of E_{fold} increases with mass accretion rate and weakly depends on plasma temperature kT_e if it is less than 10 keV.

Observationally this bulk motion effect can be seen as a non-monotonic behavior E_{fold} versus index Γ (see Fig. 4). In the 2000 observation (Fig. 5) we see only the first part of this dependence of E_{fold} vs Γ, when E_{fold} decreases and reaches its minimum value in the range of 100-120 keV, because Γ does not exceeds 2 (compare Figs. 4 and 5). Namely, we see *the strong evidence of the bulk motion effect when efold energy E_{fold} at first decreases with photon index and then reaching minimum value in the range of 50-100 keV starts to increase to about 200 keV and when index values start to saturate at* ~ 2.8. On the other hand, Farinelli & Titarchuk (2010) recently show using a number of *Beppo*SAX observation of accreting neutron stars that photon index of Comptonization spectra does not show strong evolution and, in fact, stays almost the same around 2 from the low hard to high soft states of neutron star binaries.

Laurent & Titarchuk (2010) simulated spectra of the converging flow using Monte Carlo method. If was found that the folding energy E_{fold} of the cutoff power law component first decreases and then increases as a function of mass accretion rate $\dot{m}$, which the cutoff energy reaching its minimum around $\dot{m} \sim 1$. Also they demonstrate that index of the emergent spectrum monotonically increases for $\dot{m} > 0.1$ and then saturates in complete agreement with the observed picture shown in Figure 6, where N_{bmc} is indicator of the disk mass accretion rate $\dot{m}$. Because of this monotonic behavior of index vs mass accretion rate up to the saturation level we expect that the same behavior pattern Γ vs $\dot{m}$ and consequently E_{fold} vs $\dot{m}$ should be seen in the observations. In Figure 7 we present the observed dependence of E_{fold} as a function of N_{bmc} ($\propto \dot{m}$). As one can see, the observed pattern of E_{fold} vs N_{bmc} dependence is strikingly similar to the Monte Carlo simulated folding energy evolution as a function of mass accretion rate [see Fig. 8 and details of these simulations in Laurent & Titarchuk (2010)].

Grove et al. (1998) reported the results of OSSE observations of seven transient black hole candidates : GRO J0422+32, GX 339-4, GRS 1716-249, GRS 1009-45, 4U 1543-47, GRO J1655-40, and GRS 1915-105. They found that last four objects exhibit a "power-law gamma-ray state" with a soft spectral index ($\Gamma \sim 2.5-3$) and no evidence for a spectral break. For GRO J1655-40, the lower limit on the break energy was found to be 690 keV. Although Grove et al. (1998) suggested that the HSS spectra detected by OSSE are consistent with bulk-motion Comptonization in the convergent accretion flow, latter Zdziarski et al. (2001) reinterpreted the same data and ruled out the bulk Comptonization as an origin of the HSS spectra because the emergent spectra are extended to energies up to 700 keV.

Thus the question is which instrument more accurately describes the phenomenology of the high energy cutoff, OSSE or *RXTE*/HEXTE. Answer to this question is crucial for understanding and interpretation of BH spectral signatures. In that respect we note that the typical OSSE spectrum require exposure time of order 10^5 s, i.e more than a day, whereas the PCA/HEXTE X-ray spectra presented here are results of time accumulation of a few kiloseconds, or two orders of magnitude shorter than the usual OSSE exposure. OSSE observed GRO J1655-40 in the VHS of 1996 outburst when the source was very variable on time scales of hours and longer. In this case the long accumulation time can result in a biases in the observed spectral shape. We suggest that the presence of the extended power law up to $\sim$ 700 keV in OSSE spectra can be a result of the long accumulation time scale when specific details of the spectra can be altered particularly at high energies.

Despite the fact that HEXTE is not sensitive above 300 keV, it is able to sample the source spectrum with much more detailed temporal resolution. Our analysis of the PCA/HEXTE from XTE 1550-564 indicates that VHS spectra do show exponential turnover at energies about 200 keV (see Fig. 4). Moreover, our results clearly show that the cutoff energy gradually changes from LHS through IS towards HSS. It is worth noting that Motta et al. (2009) concluded that the cutoff power law in the PCA/HEXTE spectrum of GX 339-4 is most likely due to one spectral component. Thus we rather incline to believe that HEXTE more accurately detects the hard tail of X-ray spectra, at least, up to 300 keV than that by OSSE. *In other words one can definitely see an exponential rollover at energies about 200-300 keV in HEXTE data when there is enough statistics in the data.*

In fact, there are more physical arguments in favor of the PCA/HEXTE versus OSSE observations of the hard X-ray tails in BH X-ray binaries. Namely, the dynamical time scale which is related to the magneto-acoustic oscillations of the Compton cloud (CC) is $t_d \sim 2L_{cc}/V_a$ where L_{cc} is the CC size and V_a is the magnetoacoustic velocity [see e.g. Titarchuk & Shaposhnikov (2005)]. With the assumption that the characteristic CC size L_{cc} in the HSS is of the order of $(5-10)(3R_S) \sim 10^8(m/10)$, where $R_S = 3 \times 10^5 m$ is the Schwarchild radius, m is BH mass in solar units, $V_a \sim 10^7(kT_e/1 \text{ keV})$ cm s^{-1}, T_e is Compton cloud temperature, we obtain that $t_d \sim 20[(m/10)/(kT_e/1\text{keV})]$ s. Thus, the dynamical time scale of Compton cloud t_d is only one order magnitude shorter than the PCA/HEXTE accumulation time of $\sim 10^3$ s and we rather believe that the PCA/HEXTE spectra including its turnover more precisely describe the shape of the high/soft emergent spectra than that by the OSSE spectra averaged over 2 magnitudes longer period.

5. Conclusions

We present further observational evidence supporting the theory of the bulk motion (converging) flow near accreting black holes. We show that when sufficient cooling is provided by the mass supply from the donor star, the Comptonizing media is completely cooled down and the origin of the extended cutoff power law is due to non-thermal bulk motion process. The energy of the high energy cutoff observed during 1998 outbursts from XTE J1550-564 (as well as during 2007 outburst from GX 339-4 reported by Motta et al. (2009)) behaves in striking agreement with the bulk motion scenario.

Combined with the previously reported effect of index saturation in BH X-ray binaries (Shaposhnikov & Titarchuk 2009) the cutoff energy behavior provides robust observational signature of the bulk motion region near the accreting object. As a direct consequence of the specific drain properties of the BH, this signature presents the most direct observational evidence of the existence of the astrophysical black holes.

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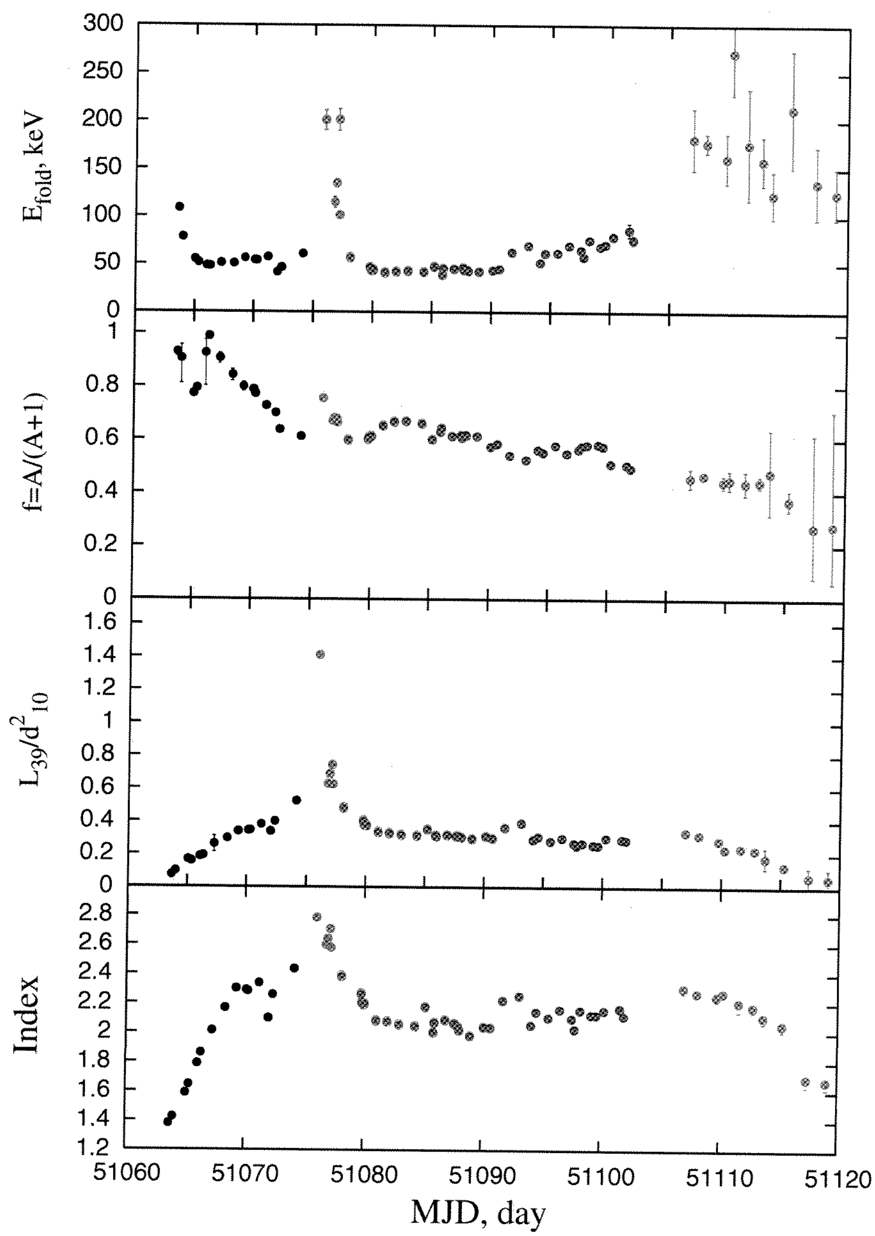

Fig. 1.— Evolution of spectral parameters during the rise part of the 1998 outburst of XTE J1550-564. LHS spectrum is shown in black, VHS is in red, IS is in blue and HSS is in orange.

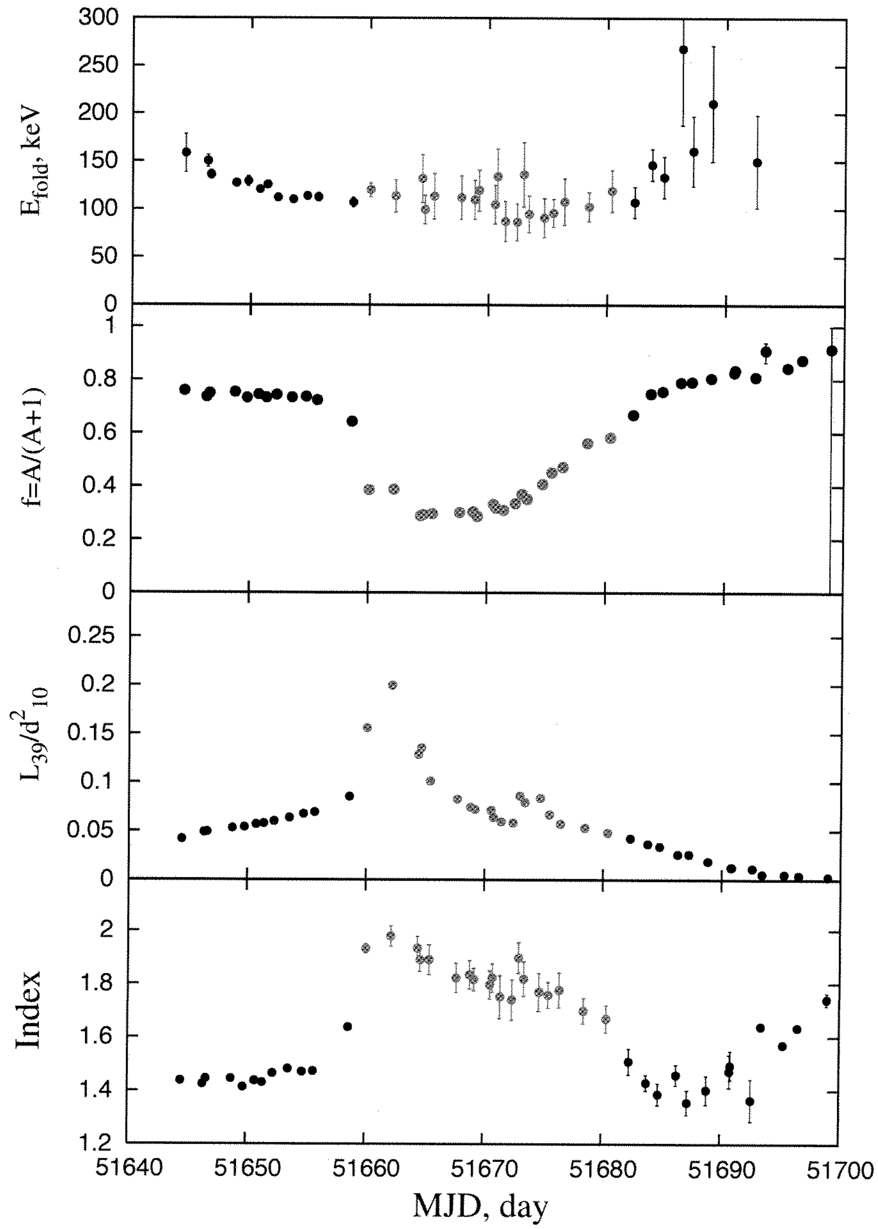

Fig. 2.— Evolution of spectral parameters during the 2000 outburst of XTE J1550-564.

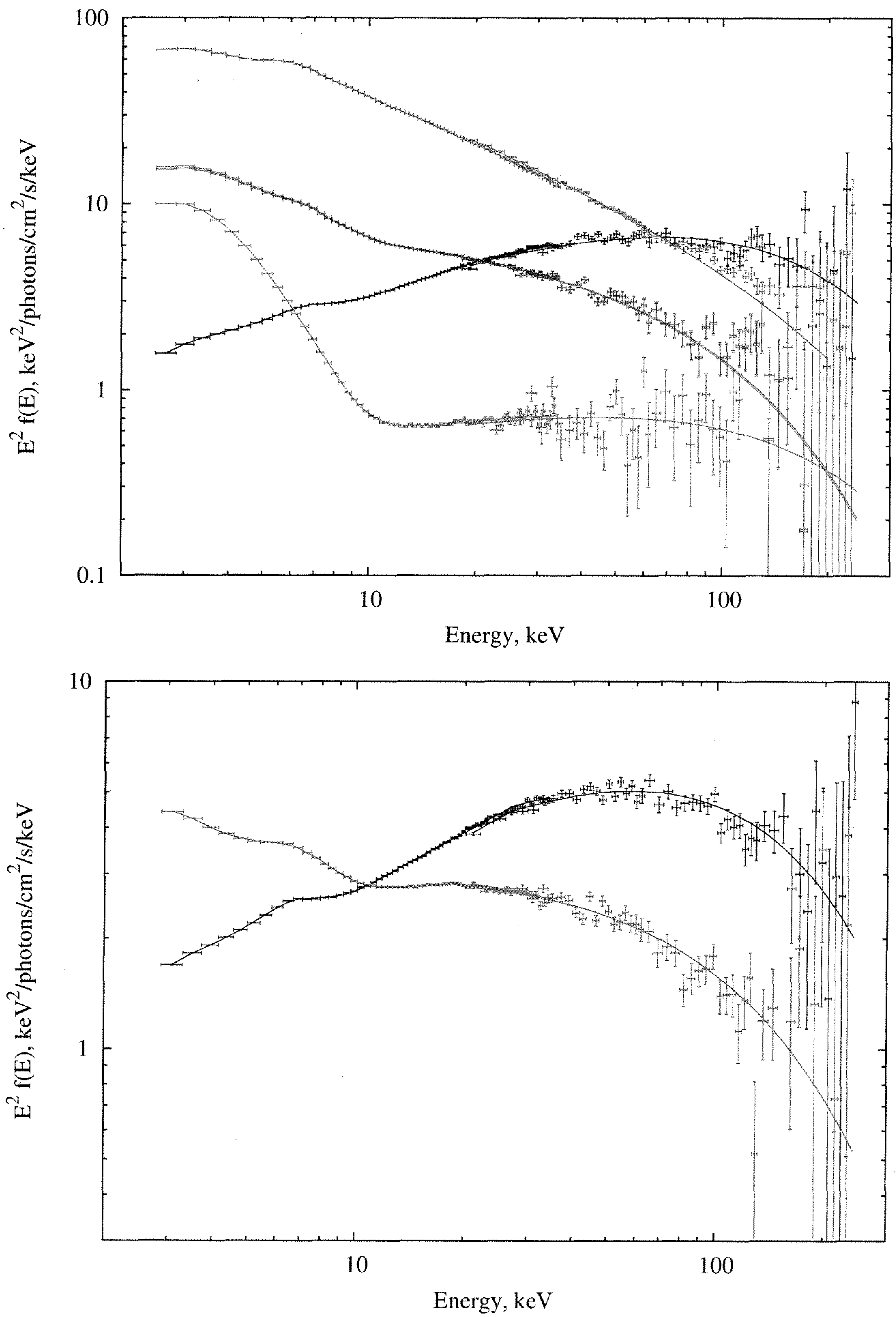

Fig. 3.— Four representative energy spectra during different stages of 1998 outburst from XTE J1550-564. LHS spectrum is shown in black, VHS is in red, IS is in blue and HSS is in orange.

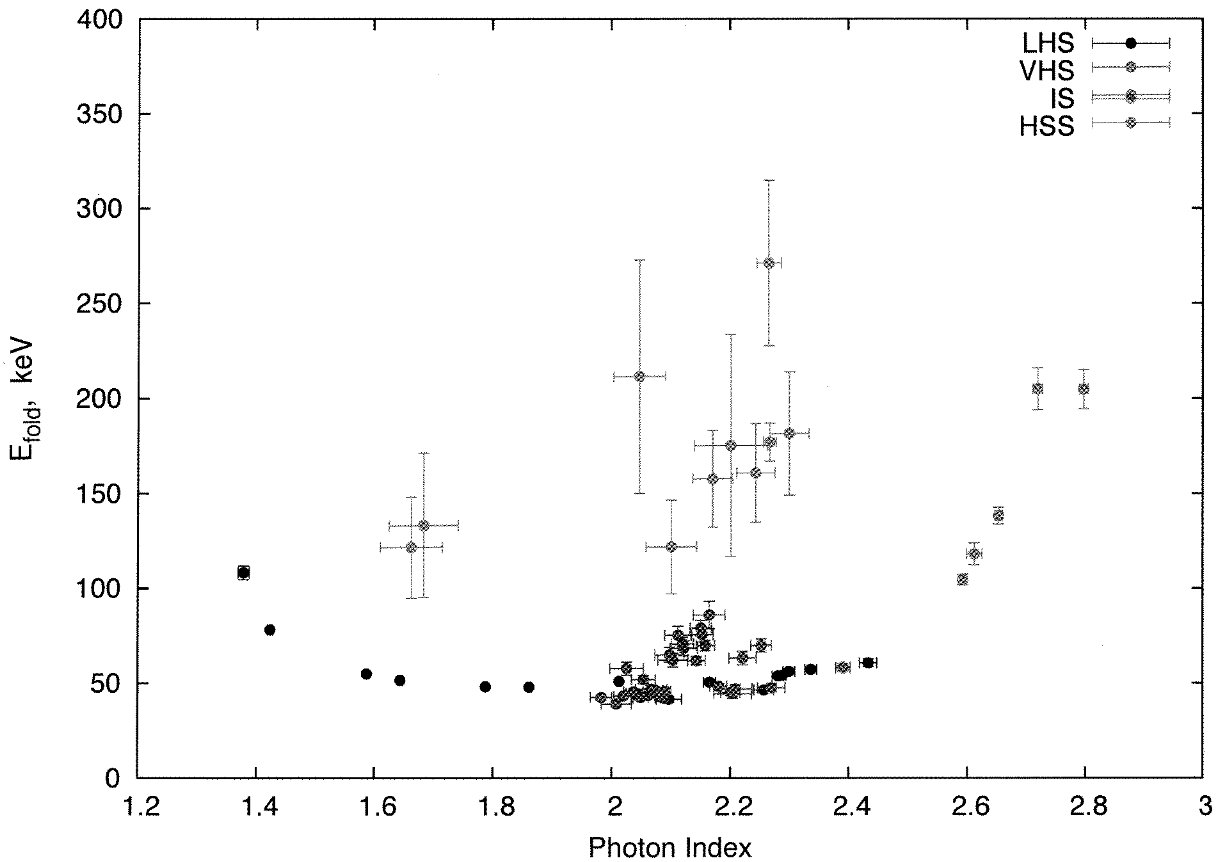

Fig. 4.— Efold energy E_{fold} versus photon index for 1998 outburst.

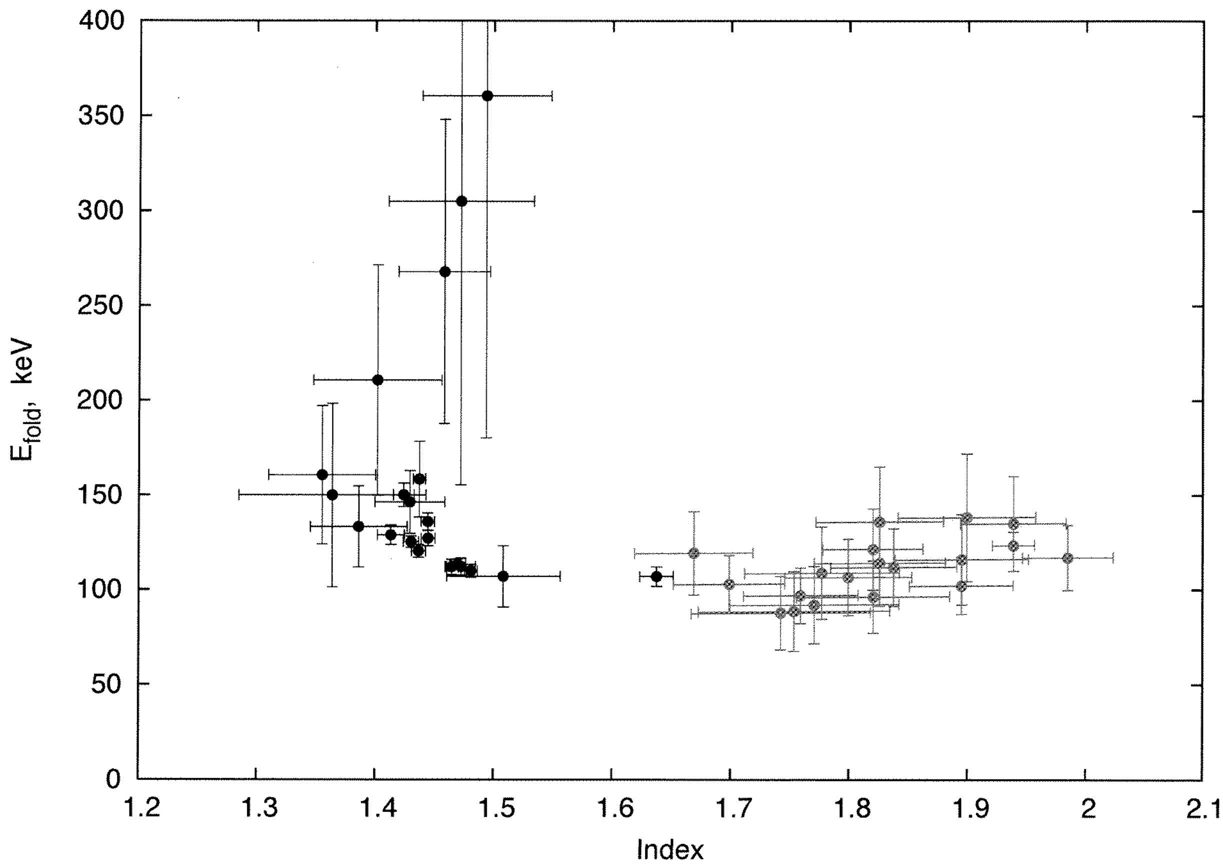

Fig. 5.— Efold energy E_{fold} versus photon index for 2000 outburst. Color legend corresponds to Fig 4.

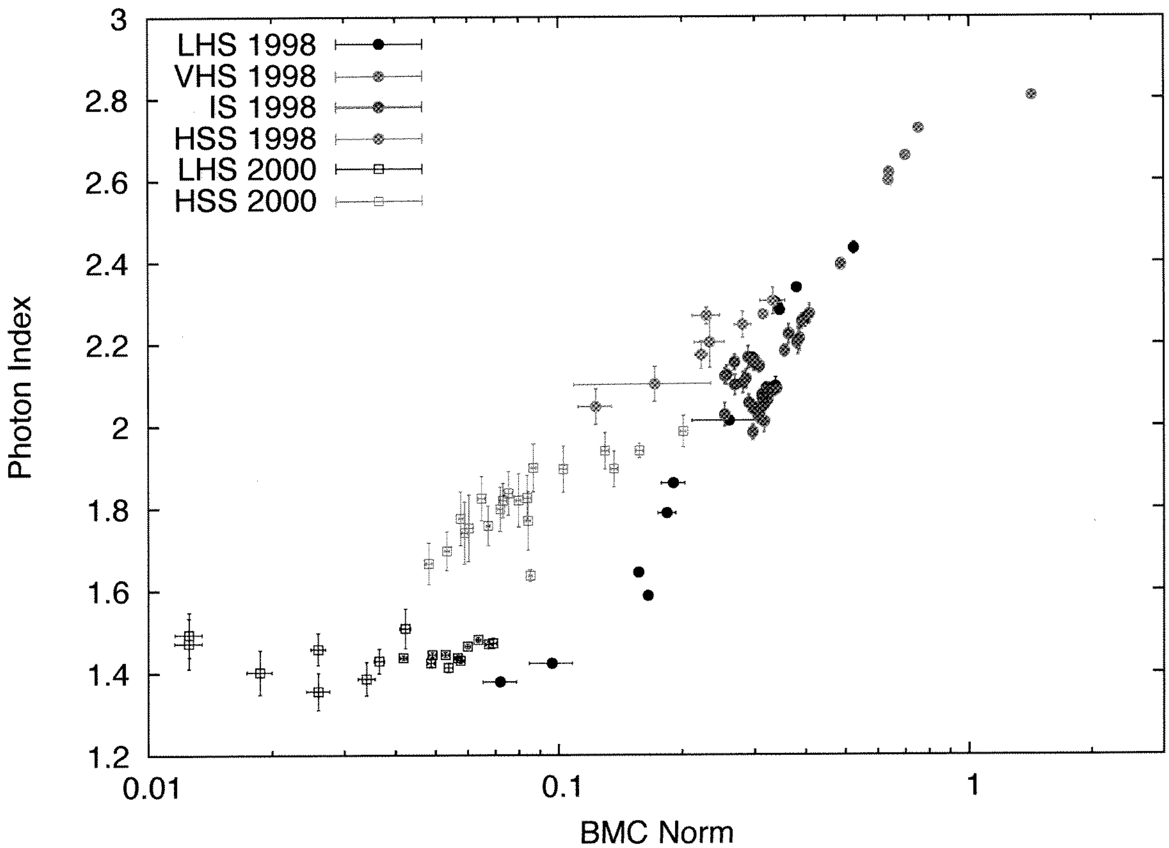

Fig. 6.— Observational correlation of photon index versus BMC normalization which is proportional to disk mass accretion. The 1998 outburst case.

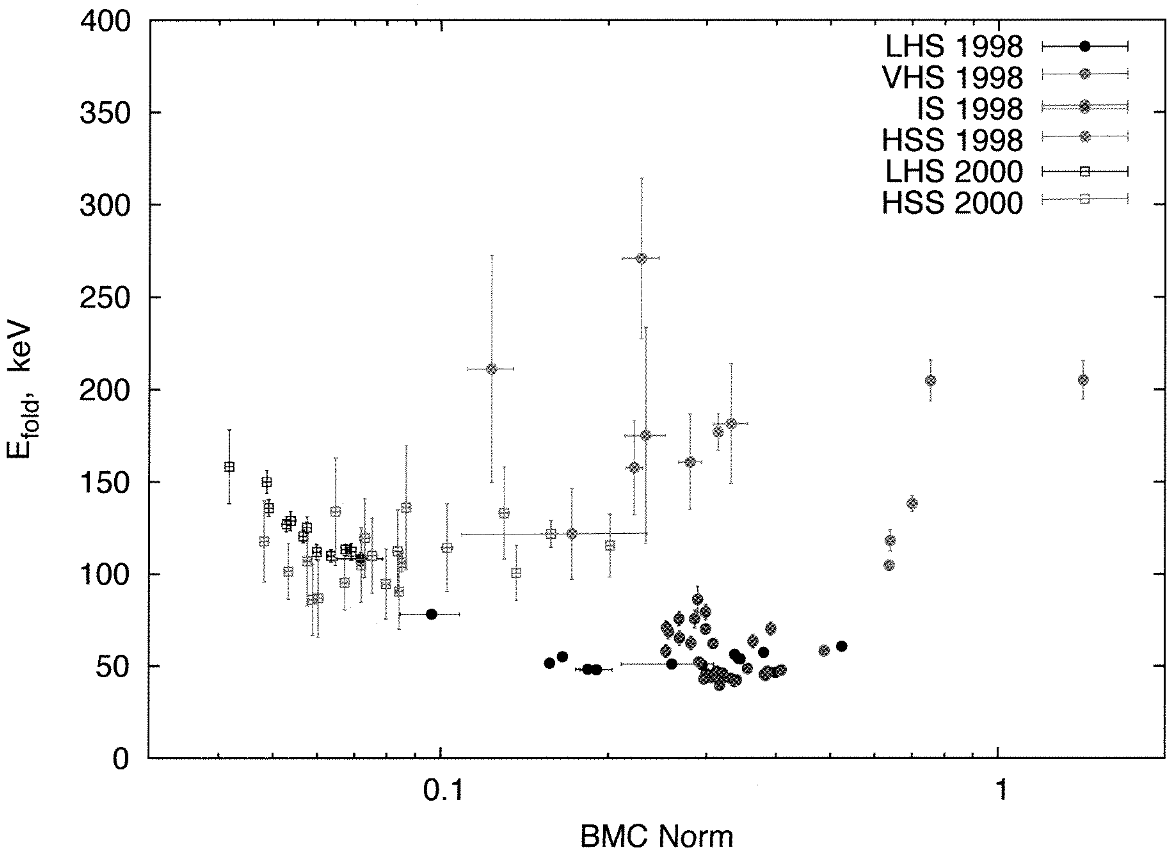

Fig. 7.— Efold energy E_{fold} versus BMC normalization which is proportional to disk mass accretion. The 1998 outburst case.

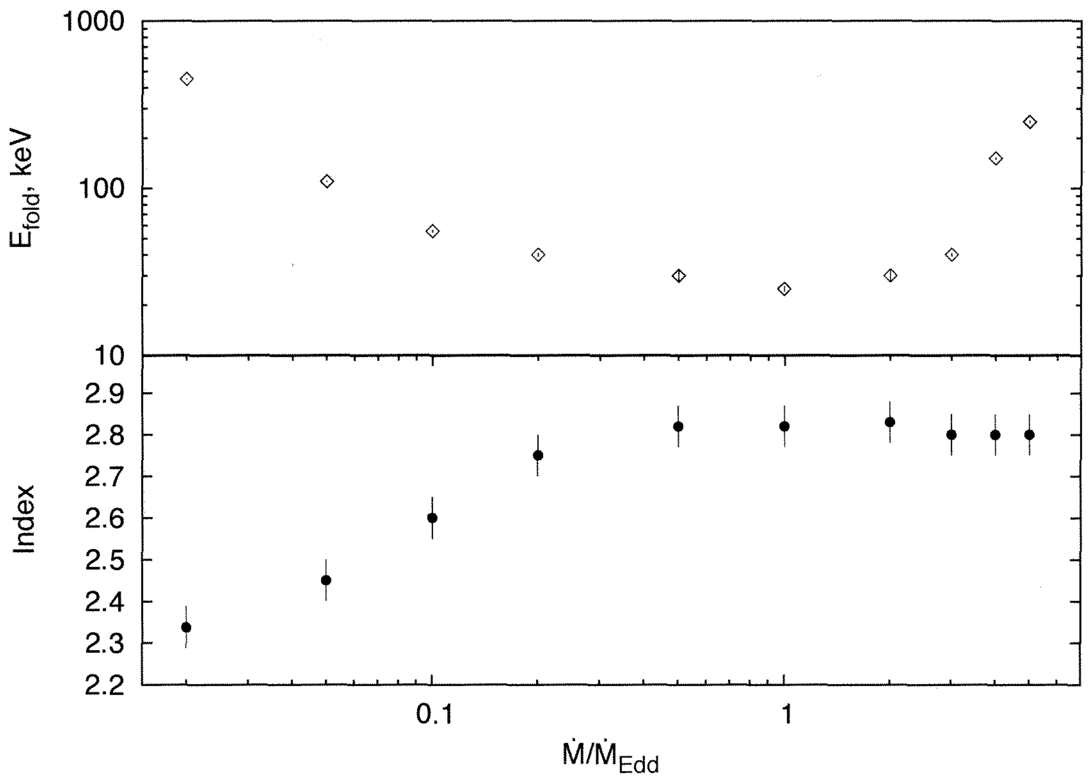

Fig. 8.— The cutoff folding energy E_{fold} (top panel) and the photon index versus mass accretion rate obtained in Monte Carlo simulations by Laurent & Titarchuk (2010).